Nuclear Instruments and Methods in Physics Research A 605 (2009) 350–352

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Letter to the Editor

CMOS pixel sensor response to low energy electrons in transmission electron microscopy

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ARTICLE INFO

Article history:
Received 26 March 2009
Accepted 27 March 2009
Available online 10 April 2009

Keywords:
Monolithic active pixel sensor
Transmission electron microscopy

ABSTRACT

This letter presents the results of a study of the response of a test CMOS sensor with a radiation tolerant pixel cell design to 80 and 100 keV electrons. The point spread function is measured to be $(13.0 \pm 1.7)\,\mu m$ at 100 keV and $(12.1 \pm 1.6)\,\mu m$ at 80 keV, for 20 μm pixels. Results agree well with values predicted by a Geant-4 and dedicated charge collection simulation.

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1. Introduction

Monolithic CMOS pixel sensors open new perspectives in fast nano-imaging through single electron direct detection in transmission electron microscopy (TEM). High-voltage electron microscopy, developed and used for high resolution imaging in the late 1970s [1] produced advances in spatial resolution, but was abandoned due to the severe displacement damage of the sample. As the displacement damage threshold is proportional to $\sqrt{E}$, there is now much interest in TEM of organic samples with energies of 80–100 keV, where recent advances in electron optics ensure deep sub-angstrom spatial resolution [2]. For example, the maximum energy transferred by an 80 keV electron to a carbon atom is 15.6 eV, which is below the threshold for knock-on damage. This makes low energy TEM necessary for atomic resolution studies of samples such as single atomic layers of carbon in graphene or carbon nanotubes [3] and in biology. There are two main issues to be considered for imaging with low energy electrons. The first is the large fluctuations in the energy deposition. The second is the degradation of the point spread function (PSF) due to the $1/E$ increase of the electron multiple scattering in the detector.

In an earlier paper [4], we presented the design of a radiation tolerant CMOS pixel cell and investigated the response of 10 and 20 μm pixels to electrons in the energy range 120 keV up to 300 keV for TEM. In this letter we extend that study to lower energies, by investigating the response to 80 and 100 keV electrons.

2. Simulation

We perform a detailed simulation of the charge deposition and signal formation in the CMOS pixel sensor based on the `Geant-4` program [5] using the low energy electromagnetic physics models [6]. The CMOS sensor is modelled according to the detailed geometric structure of oxide, metal interconnect and silicon layers, as specified by the foundry. Electrons are incident perpendicular to the detector plane and tracked through the sensor. For each interaction within the epitaxial layer, the ionisation point position and the amount of energy released are recorded.

Charge collection in the sensor is simulated with `PixelSim`, a dedicated digitisation module [7], developed in the `Marlin` C++ reconstruction framework [8], originally deployed for the International Linear Collider particle physics project. The processor starts from the ionisation points generated along the particle trajectory by `Geant-4` and stored in `lcio` format [9]. The `PixelSim` simulation models diffusion of charge carriers from their production point in the epitaxial layer to the collection diode. This provides us with full simulation of the response of each individual pixels in the detector matrix, including sensor geometry and electronics noise effects, which can be processed through the same analysis chain as the experimental data. The simulation has a single free parameter, the diffusion parameter σ_{diff}, used to determine the width of the charge carrier cloud. Its value is extracted from data by a χ^2 fit to the pixel multiplicity in the clusters of 1.5 GeV electrons since, at this energy, the multiple

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0168-9002/$ - see front matter Published by Elsevier B.V.
doi:10.1016/j.nima.2009.03.249

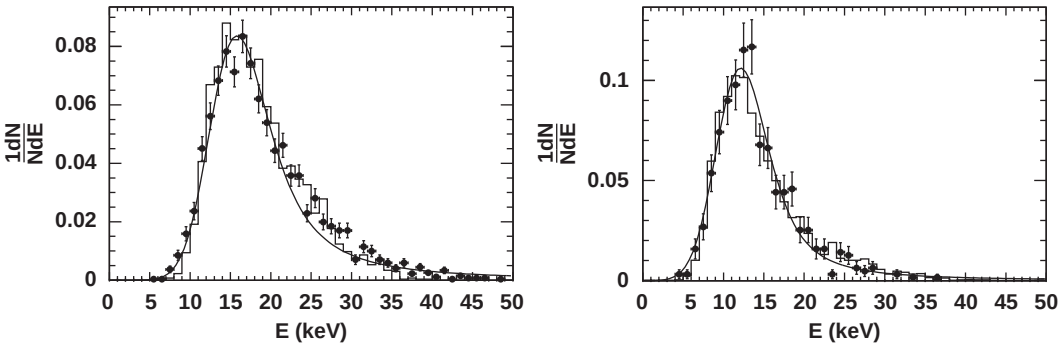

Fig. 1. Reconstructed deposited energy in a 3 × 3 pixel matrix for 80 keV (left) and 100 keV electrons (right). The points with error bars show the data and the histogram as the result of the Geant-4 simulation. The continuous line shows a Landau function convoluted with a Gaussian noise term fit to the data.

scattering contribution to the charge distribution is negligible. We find $\sigma_{\text{diff}} = (16.3 \pm 1.4)\,\mu\text{m}$, which agrees well with the diffusion length estimated from the doping in the epitaxial layer and the charge collection time [4].

3. Measurement

The detector charge-to-voltage conversion is 0.98 keV/ADC count or 26.7e^-/ADC count at 6.25 MHz readout frequency, obtained by recording the position of the 5.9 keV full energy peak of a collimated 2.2 mCi ^{55}Fe source.

We use the TITAN test column at the National Center for Electron Microscopy (NCEM) to characterise the detector response to 80 and 100 keV electrons and validate the simulation. The signal pulse height in a 3 × 3 matrix around each seed pixel having a signal-to-noise in excess of 4.5 is shown in Fig. 1 for data and simulation. The broadening of the energy distribution compared to electrons of higher energy is evident, however, the ratio of the Landau width to the Landau most probable value does not increase significantly compared to that for electrons of higher energy. We estimate the uncertainty on the number of electrons per pixel that can be reconstructed from the measured pulse height in a single pixel. We simulate a flat field illumination by generating multiple electrons hitting each pixel and reconstruct the pixel pulse height. This accounts for cross-feed between neighbouring pixels due to charge diffusion and multiple scattering. We determine the number of electrons on each pixel by dividing the simulated pixel pulse height by the average pulse height induced by a single electron and study the distribution of the reconstructed number of electrons as a function of that simulated. We find that the relative uncertainties on this number scale from 0.17 (0.14) for 10e^-/pixel to 0.12 (0.10) for 20e^-/pixel and to 0.08 (0.06) for 50e^-/pixel at 80 keV (100 keV), respectively. These results are comparable to relative uncertainties of 0.15, 0.11, 0.07 obtained for 200 keV electrons.

Finally, we determine the point spread function following the same method discussed in Ref. [4]. We reconstruct the image of a gold wire with a diameter measured to be $(59.6 \pm 0.7)\,\mu\text{m}$ and mounted parallel to the pixel columns, at a distance of $\simeq 3$ mm from the detector surface. The profile of the deposited energy in the pixels, measured across the wire allows us to determine the charge spread due to electron multiple scattering and charge carrier diffusion. We describe the measured pulse height on the pixel rows across the image projected by the wire with a box function having the same width as the measured wire diameter smeared by a Gaussian term, which describes the point spread function. The contrast factor, i.e. the ratio of maximum to minimum pulse height levels, for the pixels away from the wire shadow and for those exactly below the wire centre, respectively, are set to those observed in data and we perform a simple 1-parameter χ^2 fit to extract the Gaussian width term, which gives the estimation of the PSF. Results are given in Table 1 and Fig. 2. A good agreement is found between the measurement and the prediction from simulation. These results are compared with those obtained at higher energies, presented in Ref. [4]. It is interesting to observe how the degradation of the PSF at decreasing energies, caused by multiple scattering, reaches a plateau around 120 keV. This is due to the decrease of the electron range with the particle energy, which limits the distance over which charge can be spread. In fact, we measure a point spread function value for 80 and 100 keV electrons which is compatible with that measured at higher energies, as predicted by the simulation.This result is quite encouraging for extending the application of CMOS pixel sensors to fast TEM imaging of organic and biological samples with low energy electrons.

Table 1
Point spread function predicted by Geant 4+PixelSim and measured with data for 20 μm pixel pitch.

Energy (keV)	Geant-4+PixelSim (μm)	Data 20 μm pixels (μm)
80	12.7 ± 0.5	12.1 ± 1.6
100	13.2 ± 0.5	13.0 ± 1.7

The uncertainty quoted for simulation is the systematics from σ_{diff} that for data accounts for statistical and systematics from pixel response equalisation.

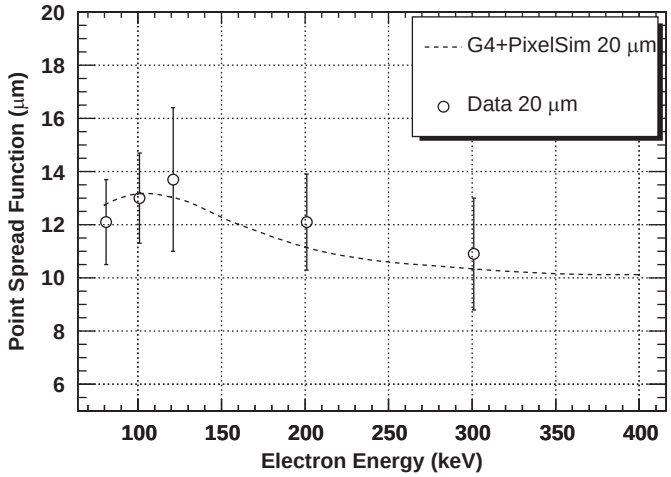

Fig. 2. Point spread function vs. electron energy with data (points with error bars) compared to simulation (lines) for 20 μm pixels. Data points from 120 to 300 keV are from Ref. [4]. The new measurements at 80 and 100 keV show the saturation of the point spread function contribution from multiple scattering in the sensor due to the reduced range of electrons as predicted by the simulation, shown by the line.

Acknowledgements

We wish to thank Thomas Duden, Rolf Erni and Zhongoon Lee. This work was supported by the Director, Office of Science, of the U.S. Department of Energy under Contract no. DE-AC02-05CH11231.

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